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Stochastic Inversion of InSAR Data to Assess the Probability of Pressure Penetration into the Lower Caprock at In Salah

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1   Stochastic Inversion of InSAR Data to Assess the

2   Probability of Pressure Penetration into the Lower

3   Caprock at In Salah

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19   **Abstract**

20   We carried out stochastic inversions of InSAR data to assess the probability that pressure

21   perturbations resulting from CO_2 injection into well KB-502 at In Salah penetrated into

22   the lower caprock seal above the reservoir. We employed inversions of synthetic data to

23   evaluate the factors that affect the vertical resolution of overpressure distributions, and to

24   assess the impact of various sources of uncertainty in prior constraints on inverse

25   solutions. These include alternative pressure-driven deformation modes within reservoir

26   and caprock, the geometry of a sub-vertical fracture zone in the caprock identified in

27   previous studies, and imperfect estimates of the rock mechanical properties. Inversions

28   of field data indicate that there is a high probability that a pressure perturbation during

29   the first phase of injection extended upwards along the fracture zone ~150 m above the

30   reservoir, and less than 50% probability that it reached the Hot Shale unit at 1500 m

31   depth. Within the uncertainty bounds considered, we conclude that it is very unlikely that

32   the pressure perturbation approached within 150 m of the top of the lower caprock at the

33   Hercynian Unconformity. The results are consistent with previous deterministic

34   inversion and forward modeling studies.

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42   **1.0 INTRODUCTION**

43   Inversion and modeling of the surface deformation caused by CO_2 injection at the In

44   Salah field in Algeria imaged using Interferometric Synthetic Aperture Radar

45   Interferometry (InSAR) have demonstrated the potential of InSAR as a powerful, cost

46   effective tool for long-term monitoring of commercial-scale geological carbon

47   sequestration in even relatively deep reservoirs. The InSAR images have been used as

48   one of the primary data sets in several inversion and forward modeling studies to map the

49   spatial distributions of subsurface changes in fluid volume and pressure and CO_2

50   saturation during the first period of active injection between 2004 and 2007 and the

51   subsequent period of well shut-in. An important consensus of these studies is that the

52   dominant flow within the reservoir in the vicinity of at least one of the In Salah wells is

53   along a sub-vertical, narrow tabular zone that intersects the injection interval, and that

54   changes in fluid pressure resulting from the injection penetrated up this zone into the

55   lower caprock above the storage complex (the sandstone reservoir and the tight sandstone

56   /siltstone unit overlaying it). However, because the vertical resolution of deformation

57   models constrained by the surface displacement data is limited, the vertical extent of the

58   pressure perturbation remains a subject of debate. The primary objective of the present

59   paper is to evaluate the influence of factors specific to In Salah on the uniqueness of

60   inverse solutions and forward models constrained by the InSAR data, and to provide

61   probability estimates of the depth of overpressure penetration. These provide a

62   quantitative measure of uncertainty that could form the basis for risk-based decision

63   making.

64

65   The In Salah project has been described in several papers (e.g. Wright et al., 2006;

66   Ringrose et al., 2009; Vasco et al., 2010), and is briefly summarized here. In Salah is the

67   world's first industrial-scale CO_2 storage project that from 2004 until 2011 injected 3.8

68   million tonnes of CO_2 captured from gas produced from the Krechba field. The injection

69   took place through three wells (Figure 1) into a ~20 m thick Carboniferous sandstone

70   formation (C10.2) on the flanks of an anticline at about 1800 m depth. The Krechba

71   stratigraphic section is summarized in Figure 2. The storage complex at In Salah

72   comprises this sandstone and the sandstone and siltstone unit (C10.3) overlying it.

73   Above that a 900 m-thick sequence of Carboniferous mudstones and shales form a lower

74   caprock seal.

75

76   Permanent-scatterer InSAR (PSInSAR; Ferretti et al, 2001) processing of Envisat data

77   carried out by Tele-Rilevamento Europa (TRE) for the period from 2003 to early 2009

78   are described in Vasco et al. (2008, 2010) and Rucci et al. (2013). This period includes

79   the first phase of injection into well KB-502 (Figure 1), and the subsequent well shut-in.

80   Ferretti et al. (2011) describe the SqueeSAR^{TM} processing technique used to produce

81   interferograms covering the second phase of injection at KB-502 beginning in November

82   2009. InSAR processing employing different techniques was also carried out by

83   MacDonald, Detwiler and Associates in partnership with Haliburton-Pinnacle (Davis,

84   2011) and by Onuma and Ohkawa (2009) and Onuma et al. (2011). General explanations

85   of the basic theory and implementation of InSAR are given in, for example, Burgmann et

86   al. (2000) and Rosen et al. (2000)

87

88   In the first study to utilize the InSAR data, Vasco et al. (2008) inverted a time series of

89   scalar line-of-sight range change (LOS) measurements between July 2003 and March

90   2007 to map fluid volume and pressure changes resulting from injection into KB-502.

91   Fluid flow and pressurization were assumed to be restricted to the primary C10.2

92   reservoir. However, in a later study Vasco et al. (2010) interpreted the distinctive

93   double-lobe pattern of InSAR range change produced by injection into KB-502 as

94   suggestive of pressure-driven tensile (Mode I) opening of a NW-striking fault or fracture

95   zone within and/or above and below the reservoir horizon (see also Morris et al., 2011),

96   and inverted the data for Mode I opening within this zone as well as isotropic volume

97   changes within the reservoir. The inferred presence of such a zone of high permeability is

98   consistent with the conclusions of Ringrose et al., (2009) and Iding and Ringrose (2010)

99   that the dominant flow within the reservoir in the vicinity of KB-502 was along a near-

100   vertical zone oriented NW, in the direction of maximum horizontal stress. This

101   interpretation was subsequently supported by the identification of a NW-trending

102   lineament on 3D seismic surfaces at the top of the C10.2 and on shallower horizons up to

103   the Hot Shale (Figure 2) (Gibson-Poole and Raikes, 2010). The ~4 km long, ~300-400 m

104   wide lineament intersects the trace of the horizontal section of KB-502 and coincides

105   with the trough between the lobes in the InSAR pattern. A similar feature is seen

106   extending SE from KB-503 on the C20.1 and C20.4 surfaces. The origin of the

107   lineaments has not been determined conclusively, and their definition at shallower depths

108   is equivocal.

109

110   Interpretation of possible fault or fracture zones - and perhaps zones of increased fluid

111   saturation - raised the possibility of CO_2 leakage conduits within the lower caprock seal.

112   Therefore, subsequent inversion and modeling studies have focused on attempts to

113   constrain the characteristics of these features, the modes and amounts of deformation

114   within them, and their dimensions. Because the seismic data – at least as currently

115   processed - do not reliably resolve the sub-vertical linear features at shallower depths in

116   the lower caprock up to and including the Hercynian Unconformity (HU), recent studies

117   have focused in particular on determining the vertical extent of potential high

118   permeability zones within the lower caprock.

119

120   Rucci et al. (2013) inverted two-component (quasi-vertical and quasi-EW) surface

121   displacements derived from one ascending and one descending InSAR pair (see Rucci et

122   al. 2013; Wright et al., 2004) spanning the 2004-2008 time interval. They found that the

123   best-fitting solutions combined isotropic volume change and tensile opening confined to

124   100 m-wide, NW-striking sub-vertical zones intersecting each of the three injection wells

125   (although they acknowledge that adding volume change within the reservoir may further

126   improve the data fits).   The combined solution for KB-502 and KB-503 yields a

127   maximum net opening in the zone intersecting KB-502 of approximately 35 cm, or a

128   lateral strain of 3.5×10^{-3}. The zone of significant opening (>4 cm) extends about 4 km

129   SE-NW, and from 400-450 m above the reservoir to 300-350 m below it. The maximum

130   cumulative dilation is much greater than the 5-6 cm in the solution of Vasco et al. (2010),

131   but the lateral strain is similar to the 3.2×10^{-3} obtained by InSAR-constrained hydro-

132   mechanical modeling by Rutqvist et al. (2011) using a vertical zone 50 m wide extending

133   200 m above the injection horizon.

134

135   Further, detailed forward modeling studies that incorporated a narrow vertical permeable

136   zone above the KB-502 reservoir were carried out by Shi et al. (2012) and Rinaldi and

137   Rutqvist (2013). Shi et al. (2012) concluded that tensile opening within a 4 km-long,

138   NW-trending fracture zone (based on Vasco et al., 2010) initiated within the reservoir

139   around November 2005. History matching of the calculated bottom hole pressure

140   indicated that pressurization and fracture opening was confined to the reservoir interval

141   until March 2006 and then propagated upward into the lower caprock to attain, in a

142   scenario based on Vasco et al. (2010)) and Morris et al. (2011*)*, a total height of 360 m

143   within and above the C10.2 reservoir by July 2007. Although the modeling results are

144   consistent with the development of the surface uplift pattern over time, the equivalent

145   fracture opening through March 2006 is sub-millimeter, at least three orders of magnitude

146   less than that estimated by Rucci et al. (2013) through 2008. However, Shi et al. (2012)

147   argue that this estimate corresponds to only the first few months of fracture opening and

148   also that the equivalent total aperture change would be larger if numerous fractures were

149   involved.

150

151   Rinaldi and Rutqvist (2013) conducted time-dependent, hydro-mechanical modeling of

152   the KB-502 injection constrained by an InSAR range-change time series covering the

153   period 2003-2009 and the pressure and injection rate history at KB-502. Like Shi et al.

154   (2012), Rinaldi and Rutqvist interpreted the injection rate and pressure history and the

155   appearance of the double lobe in the InSAR range change as evidence for sudden

156   pressure-induced fracture opening. Based on Vasco et al. (2010) and the 3D seismic

157   interpretation, a vertical, 3.5 km-long, NW-trending, orthotropic fracture or damage zone

158   was activated in the lower caprock after the first five months of injection. Although they

159   do not report changes in fracture aperture, their base model, in which an 80 m-wide

160   fracture zone extended 350 m above the reservoir, produced good matches to the pattern

161   of cumulative range change in the vicinity of the double lobe and to the transient

162   evolution of the ground displacement at a point over KB-502 through the well shut-in in

163   July 2007. A series of sensitivity tests explored the effect of varying the permeable

164   fracture zone length, width and, in particular its height. Extending the fracture zone 700

165   m above the reservoir produced much larger range change amplitudes than observed,

166   while allowing it to penetrate the HU at 900 m and connect with the shallow aquifer

167   produced much smaller amplitudes and a poor fit to the range-change time series.

168

169   While there is a consensus among the inversion and modeling studies that overpressure

170   and fluid penetration into the lower caprock at KB-502 was confined to a narrow zone

171   that probably does not extend more than ~400 m above the reservoir, all of the papers

172   acknowledge that the inversion solutions or modeling results are subject to significant

173   uncertainties. These stem from the inherent non-uniqueness in using surface

174   displacements to constrain sources of subsurface deformation and fluid flow. Non-

175   uniqueness arises chiefly from tradeoffs among source location and geometry - and

176   particularly source depth -, the mode(s) and strengths of the deformation sources (Rucci

177   et al., 2013), flow properties (Shi et al., 2012; Rinaldi and Rutqvist, 2013), and the elastic

178   properties of the reservoir and overburden (Vasco et al., 2010). The deformation modes

179   can include pressure-driven isotropic volume change, tensile opening, and possibly shear

180   displacement and shear-induced dilatation. In other words, deformation sources located

181   at different depths and of different sizes and strengths can produce similar surface

182   deformation patterns. Non-uniqueness can, in general, only be reduced by adding

183   independent prior constraints on the model parameters. Consequently, the accuracy of an

184   inverse solution or forward model depends heavily upon the known or assumed

185   constraints.

186

187   The chief independent constraints on the location and geometry of the fault/fracture zones

188   used in the inversions by Vasco et al. (2010) and Rucci et al. (2013) and adopted by

189   Rutqvist et al. (2011), Shi et al. (2012) and Rinaldi and Rutqvist (2013), are the linear

190   features identified in the 3D seismic. Vasco et al. and Rucci et al. further adjusted the

191   lateral dimensions and dips of the fault/fracture zones to provide initial best fits to the

192   InSAR displacements themselves, so these constraints are not entirely independent of the

193   data and are themselves subject to tradeoffs.

194

195   Vasco et al. (2010) demonstrated that the elastic model of the reservoir and caprock can

196   be a significant source of uncertainty in inverse and forward model solutions. They

197   derived a 20-layer elastic model from P- and S-wave velocity logs and density profiles

198   from several of the Krechba wells (this model was also used by Rucci et al., 2013), but

199   available velocity logs [provided to researchers by the In Salah Joint Industrial

200   Partnership (JIP)] are of generally poor quality above the lowermost caprock (C10.3).

201   Furthermore, it is difficult in general to relate the dynamic estimates derived from seismic

202   velocities to appropriate, field-scale static moduli (e.g. Fjaer, 2009; Li and Fjaer, 2012),

203   which are therefore inherently uncertain. The same uncertainties apply to the six-layer

204   model (Gemmer et al., 2010) used by Rutqvist et al. (2011) and Rinaldi and Rutqvist

205   (2013).

206

207   The published deterministic inversion studies produced a single solution that provides the

208   best fit to the data along with formal variance estimates within the known or assumed

209   constraints on the model, and subject to the particular regularization scheme imposed to

210   stabilize the solution. The solutions described above do not consider uncertainties in

211   model parameters that are fixed *a priori*, and so are not able to explore alternative

212   solutions permitted by the data. The forward models similarly arrive at best-fit solutions

213   by trial and error. Rinaldi and Rutqvist (2013) did, however, demonstrate that end-

214   member models provide poor fits to the observations, particularly if the fracture zone and

215   migration of CO_2 are not confined below the HU at ~900 m depth.

216

217   In order for inversion or modeling results to be of maximum use in evaluating the

218   performance of an injection operation and in planning future strategy, uncertainty

219   estimates on the solutions are needed from which the reliability of the results can be

220   assessed. Ideally, this requires a comprehensive exploration of the parameter space (i.e.

221   both the prior constraints and the free model parameters) to describe the distribution of

222   alternative models that are the most consistent with the data. In this study we accomplish

223   this by using a Markov Chain-Monte Carlo (MCMC) stochastic inversion method that

224   systematically searches the model space by sampling from uncertainty distributions on

225   the parameters that constitute prior constraints. We first carried out forward modeling

226   and inversions to examine the sensitivity of solutions to uncertainties in assumed prior

227   constraints and the set-up of the inversion problem specific to the situation at In Salah.

228   Guided by these initial studies, we then carried out stochastic inversions of the InSAR

229   data to derive quantitative estimates of the probabilities that the pressure perturbation

230   driven by injection into KB-502 reached different depths within the lower caprock.

231

2.0 INVERSION METHOD

233   Here we provide a general overview of the MCMC stochastic inversion method.

234   Adaptation of the method for application to the specific inversion problem at In Salah is

235   described in more detail in the next section.

236   The inverse problem can generally be described by letting D and X denote the data and

237   model spaces, respectively. Then suppose that there exists a mapping G such that:

238 $$d = G(x) \qquad (1)$$

239   The goal is to find models x_0 that correspond to the set of observations, d_0. The range

240   of possible solution models, X, is limited by prior knowledge.

241   Our implementation of MCMC is a derivative of the Metropolis-Hastings algorithm as

242   described by Mosegaard and Tarantola (1995), and is discussed in detail by Ramirez et al.

243   (2005). The inversion approach uses a Markov chain process to control random sampling

244   of the model space, which is effected by proposing a large number of trial models

245 (realizations), x_0. Within this framework, the solution to the inverse problem is a

246 Bayesian estimate of the posterior probability density function (pdf) defined over the

247 space of possible models, X. Then, for any potential solution $x_0 \in X$, the method will

248 provide an estimate of the probability that x_0 is the true state of the underlying system.

249 The MCMC simulation algorithm proposes sample models according to the unknown

250 posterior distribution. Simulated data are calculated by running each proposed model

251 through an appropriate computational forward model to calculate a measurable quantity

252 that corresponds to the observed data. The likelihood $L(x_0)$ that a given model $x_0 \in X$

253 produced the observed data is calculated based on the fit of the simulated data to the

254 observations, subject to the prior constraints. Based upon this likelihood, an importance-

255 sampling algorithm incorporating a randomized decision rule accepts or rejects the model

256 for inclusion in the posterior distribution. The outcome of this decision is also used to

257 determine how the next trial model is selected. This procedure is repeated over typically

258 ~10^5 trials until the chains converge to a stable solution; i.e. all Markov chains are

259 sampling from the posterior distribution. The final inverse solution is the posterior pdf

260 over the range of the alternative models that are consistent with the measured data and

261 prior information, which provides a comprehensive description of uncertainty. Therefore,

262 the stochastic inversions provide quantitative estimates of the reliability and uniqueness

263 of the solutions that can be obtained from the data and prior constraints.

264

265 MCMC is similar to deterministic inversion (e.g. Rucci et al., 2013) in that both

266 approaches propose trial models and use a forward solver to calculate responses at the

267 observation points that are compared with the data. However, the two approaches differ

268 in how the trial models are updated and in the form of the final solution. Specifically, the

269 MCMC random model generator replaces the deterministic updating scheme, and the

270 MCMC solution is a pdf defined over the model space whereas each deterministic

271 inversion selects a single model that best explains the data.

272

2.1 Adaptation of MCMC to Inversion of In Salah InSAR Data

273

274

275   In the case of In Salah each source model is a 3D distribution of fluid overpressures

276   (pressure plume) induced in the subsurface by CO_2 injection. Prior knowledge is

277   provided by the injection pressure history, the location of the injection interval, and well

278   and geophysical data on both the locations and geometries of the reservoir and possible

279   high permeability zones in the lower caprock and rock mechanical properties. The

280   location of the injection interval and the injection pressure govern the generation of

281   randomized pressure plume realizations.

282   The base structural model of the reservoir and caprock in the vicinity of well KB-502 is

283   shown in Figure 3. The reservoir is modeled as a 20 m-thick layer. Based on well and

284   seismic data (Vasco et al., 2010; Morris et al., 2011), a NW-trending, 500 m-wide

285   vertical zone of potentially enhanced permeability intersects the reservoir and extends

286   through the caprock to the HU at 850 m depth. The caprock, reservoir and underburden

287   are treated as an homogeneous elastic half-space with depth-averaged moduli based on

288   the Statoil six-layer reference model as presented in Rinaldi et al. (2013, Table 2).

289

290   Figure 4 shows the computational steps in the MCMC procedure as adapted for In Salah

291   inversions. Realizations of 3D pressure plumes are built within the structural model from

292   one or more contiguous ellipsoids (Figure 4, step A). The ellipsoids represent either

293   zones of isotropic volumetric inflation/deflation or, by constraining one axis of the

294   ellipsoid to be very small, deformation of planar fracture-like sources. The ellipsoids can

295   rotate about any axis, translate, change size and ellipticity and change pressure from one

296   trial source configuration to the next. The number of ellipsoids in a given plume and the

297   overpressure values assigned to each ellipsoid can change from iteration to iteration.

298   Each ellipsoid is mapped to a set of nodes in the 3D inversion grid, and each node is

299   treated as a point pressure-driven deformation source within the plume.

300

301   At least one of the ellipsoids in a proposed overpressure plume is connected to the

302   injection interval within a given injection well. To ensure that the number of degrees of

303   freedom remains constrained, all of the grid cells in each ellipsoid are assigned a discrete

304   category value representing fluid overpressure at each iteration. For example, if the set of

305   category values for overpressure is $\{A, B, C\}$, then: $A \rightarrow \Delta P_1, B \rightarrow \Delta P_2, C \rightarrow \Delta P_3$,

306   where the ΔP_i represent discrete, non-zero overpressure values assigned to grid nodes

307   located within an ellipsoid. The remaining grid nodes are assigned zero overpressure.

308   The maximum allowable overpressure is the injection bottom hole pressure.

309

310   Point deformation sources can be isotropic volume changes (henceforth referred to as

311   dilatational sources) or tensional opening/closing (Mode I). In general, isotropic volume

312   change is more likely in porous media such as the reservoir layer and tensional

313   opening/closing more likely in fault or fracture zones. We did not include pressure-

314   activated shear sources because the trend of the fault/fracture zone suggested by the

315   seismic and InSAR data is NW, along the direction of maximum horizontal compressive

316   stress, and therefore as a whole is not favorably oriented for shear activation. It is

317   conceivable, however, that the zone contains *en echelon* arrays of small faults or fractures

318   that are favorably oriented for shear activation, so this model could be investigated in a

319   future study.

320

321   The mode of deformation assigned to each point source depends on its location on the

322   grid. Arbitrarily-shaped inversion grid sectors are specified, each of which is assigned a

323   specific deformation mode. For example, we could specify that point sources located

324   within the horizontal reservoir layer are dilatational and, if the pressure plume extends

325   within an enhanced permeability zone into the caprock, those within the zone are

326   tensional. The strikes and dips of tensional sources can be fixed at user-specified values

327   or can vary according to the orientation of the ellipsoids within which they are located.

328

329   An initial decision to accept or reject a pressure realization is based on the consistency of

330   the proposed model with the base model (Figure 4, step B).   In the base model it is

331   assumed *a priori* that pressure changes have a high probability of occurring in the

332   reservoir, a moderate probability of occurring in the potential vertical fault/fracture zone,

333   and a very low probability of occurring elsewhere. Figure 3 illustrates how these

334 probabilities are represented on the computational grid. Grid nodes that have a non-zero

335 probability of experiencing pressure changes as a result of injection are shown in either

336 green or red, and zero-probability nodes are rendered transparent. For example, in the

337 model shown pressure changes are twice as likely to occur within the reservoir horizon

338 (red nodes) than within the vertical fracture zone (green nodes). Proposed pressure

339 plumes that encompass transparent nodes are penalized whereas models that encompass

340 green or red nodes are encouraged.

341

342 The accept/reject decision employs the Metropolis-Hastings algorithm mentioned above

343 using likelihoods calculated from the fit of the proposed realization to the node

344 probabilities in the base model. Grid nodes having non-zero overpressure in the

345 realization are assigned a value of 1 while all other nodes are set to zero. The likelihood

346 is calculated by comparing these node values to the corresponding base model node

347 probabilities. Proposals that are fully contained within the base structural model yield the

348 largest likelihoods, the likelihood falling off in proportion to the fraction of the model

349 realization that falls outside the base model. If the current proposal is rejected, then the

350 inversion process reverts back to step A, where a new realization is generated by

351 perturbing the last trial to be accepted according to a randomized rule (see Ramirez et al.,

352 2005). If the proposal is accepted, synthetic InSAR data are calculated at the surface

353 observation points by summing the displacements generated by the pressure-driven point

354 deformation sources according to the deformation modes assigned to each node. The

355 elastic moduli used in these calculations are randomly sampled from a prior distribution.

356 The forward calculations are carried out using the Lawrence Livermore National

357 Laboratory (LLNL) code SYNEF (unpublished), which computes displacements, tilts,

358 strains and stresses throughout a 3D linear elastic half-space employing, in the present

359 case, Green's functions derived by Okada (1985, 1992) for dislocations embedded in an

360 homogeneous elastic half-space. Both InSAR line-of-sight range change and quasi-

361 vertical and quasi-EW displacement components can be calculated, given the SAR

362 acquisition geometry (see Rucci et al., 2013).

363

364 Both isotropic volume change and Mode I opening are calculated from pressure change

365 without considering poroelastic effects. Mode I displacements are derived approximately

366 from the opening of an equivalent pressurized elliptical crack having the same surface

367 area and internal volume as the dislocation. The opening displacement (i.e. relative

368 displacement of the two walls) of a flat elliptical crack lying in the $z=0$ plane under

369 uniform internal pressure is given by (Green and Sneddon, 1949; Mura, 1987))

370
$$u_z(x,y) = \frac{2(1-v)}{\mu} \frac{b}{E(k)} \left[1 - \frac{x^2}{a^2} - \frac{y^2}{b^2} \right]^{\frac{1}{2}} p \qquad (2)$$

371 where a and b are the semi-major and –minor axes of the ellipse, respectively, v

372 Poisson's ratio, μ the shear modulus, p the pressure, and $E(k)$ a complete elliptical

373 integral of the second kind. The opening is elliptical with maximum displacement at (x,y)

374 = (0,0) given by

375
$$u_z^0 = \frac{2(1-v)}{\mu} \frac{b}{E(k)} p \qquad (3)$$

376 The uniform opening of the equivalent dislocation can then be calculated as

377
$$u_z^d = \frac{2}{3} u_z^0 \qquad (4)$$

378

379 The same procedure as in step D (Figure 4) is employed in the final decision to accept or

380 reject a realization based on a likelihood calculated from the fit of the synthetic InSAR

381 data to the observations (Figure 4, steps F and G). Proposed pressure models accepted at

382 this stage become part of the posterior distribution.

383

384 # 3.0 APPLICATION TO IN SALAH

385 We use MCMC to systematically assess uncertainties in inverting InSAR-derived surface

386 displacements to map the evolution of the pressure distribution from injection at In Salah

387 well KB-502. Our primary focus is on assessing factors that influence the vertical

388 resolution attainable with the available data and prior constraints. The study is conducted

389 in three parts: (1) Sensitivity analyses using synthetic reservoir and caprock models to

390 represent likely reservoir scenarios; (2) stochastic inversion of synthetic data to evaluate

391 the impacts of various sources of uncertainty; and (3) stochastic inversions of field data to

392 estimate the probabilities that the pressure plume penetrated to different depths within the

393 caprock and to different distances laterally within and above the reservoir.

394 *3.1 Synthetic models*

395 *3.11 Sensitivity Analyses using Candidate In Salah Scenarios*

396 As discussed in the Introduction, the ability of InSAR data to resolve the extent of

397 overpressure or fluid penetration into the lower caprock above the In Salah reservoir is

398 inherently limited, but supplying additional prior constraints on the inverse problem can

399 reduce the trade-offs responsible for non-uniqueness and hence improve vertical

400 resolution. In the simple synthetic analyses described here we examine the sensitivity of

401 surface displacement patterns and amplitudes to prior constraints on the characteristics

402 and distributions of deformation sources and overburden properties in order to evaluate

403 their potential effectiveness in reducing non-uniqueness in inverse solutions. The surface

404 displacement patterns were calculated using analytic Green's function solutions

405 implemented in the SYNEF code described earlier..

406

407 We consider first the sensitivity of surface displacements to selection of the deformation

408 modes that characterize different parts of the overall plumbing system. As argued earlier,

409 the two most likely modes of deformation resulting from injection at In Salah are

410 volumetric dilatation and tensional opening in Mode I. Dilatation is commonly

411 associated with fluid flow through porous media, while Mode I opening occurs when

412 increased fluid pressure forces apart the opposite faces of fractures and faults (i.e. the

413 displacement is normal to the fracture plane). Therefore, likely In Salah scenarios are

414 those that include dilatational deformation within the relatively permeable C10.2

415 reservoir together with fracture opening within the vertical zone interpreted from the 3D

416 seismic data. Although both modes of deformation may occur both within the reservoir

417 and caprock (e.g. Shi et al., 2012; Rucci et al., 2013), we examine cases in which only

418 one deformation mode is active in each zone. Our objective is to evaluate whether

419 changes in the InSAR pattern resulting from the different scenarios are sufficiently

420 distinctive to discriminate between the scenarios, and particularly to resolve the height of

421 the pressure perturbation above the reservoir. We also examine the sensitivity to

422 overburden elastic properties, and evaluate the resolving power of two-component

423 displacement data compared with scalar LOS range changes.

424

425 *3.12 Distribution of Dilatational and Opening-mode Deformation Sources*

426 Figure 5 shows plan and perspective views of the three synthetic models used for this

427 study. The green and pink elements indicate the pressurized region in the reservoir and

428 caprock fracture zone, respectively. Model 1 assumes that the over-pressurized zone is

429 fully contained within the reservoir, so that only green elements contribute to the

430 deformation field. Models 2 and 3 assume that the over pressured zone extends from the

431 reservoir 300 m and 940 m into the lower caprock, respectively, so that green and pink

432 elements both contribute to the deformation.

433

434 Figure 6A shows InSAR LOS displacements calculated from Models 1 to 3 for a

435 deformation scenario in which the mode of deformation in both the reservoir and caprock

436 is dilatational. The three panels show how the surface range-change pattern varies as the

437 overpressurized zone migrates upwards from the reservoir into the lower caprock. The

438 pattern becomes more elongated SE-NW as the pressure plume migrates upwards along

439 the fracture zone, and range change amplitudes increase significantly. Since there is only

440 a modest change in the InSAR pattern, particularly between Models 1 and 2, the primary

441 indicator of upward pressure migration when only dilatation drives the deformation is an

442 increase in the overall amplitude of the InSAR signal. However, higher amplitudes could

443 also be produced by increasing the reservoir pressure without significant migration up the

444 fracture zone, and this tradeoff degrades the ability to resolve the vertical extent of the

445 plume.

446

447 Figure 6B corresponds to a scenario that has only opening-mode sources in both the

448 reservoir and damage zone. All three synthetics exhibit the double-lobed pattern seen in

449 the InSAR LOS data above KB-502 (Vasco et al. 2010), showing that such a double-lobe

450 pattern can be created even by areally distributed Mode I sources confined to the

451   reservoir layer. Even though the maximum amplitude increases (in these synthetics)

452   from 0.3 mm to 5 mm, the change in the displacement pattern as the pressure anomaly

453   migrates upwards into the lower caprock is relatively slight. Therefore, the same tradeoff

454   between overpressure and depth applies to this scenario as to the first, suggesting that in

455   general it would be difficult to resolve the pressure plume's vertical extent when the same

456   mode of deformation occurs within both the reservoir and damage zone.

457

458   The third scenario (Figure 6C) has only dilation in the reservoir and fracture opening

459   within the lower caprock damage zone. This is the same basic model as that used by

460   Vasco et al. (2010). In this case there are significant changes in the range-change pattern

461   as the pressure anomaly migrates upwards into the lower caprock, even though the

462   amplitude changes are relatively small. The changes in the LOS displacement pattern are

463   less likely to be produced by tradeoffs between overpressure magnitude and caprock

464   penetration, which suggests that it in this dual-source scenario the InSAR data can

465   provide improved constraint on the vertical extent of a pressure perturbation.

466

467   Figure 7 compares the observed range change above KB-502 between March and July

468   2007 with synthetics calculated from dual-source and opening-mode only scenarios. All

469   three images show double lobed patterns having similar orientations. However, the dual-

470   source scenario produces an InSAR image that is most similar in both its pattern and

471   amplitude to the observations, while the opening-mode only scenario produces a

472   subsidence trough that is not present in the real data. These comparisons suggest that the

473   combination of dilatational and opening-mode sources described above is one model that

474   is compatible with the observations, in which case the InSAR data should provide a

475   modest degree of constraint on the pressure distribution at depth.

476

477   *3.13 Sensitivity to Elastic Properties*

478   The sensitivity of surface displacements to the elastic property model is illustrated in

479   Figure 8. The curves show LOS displacement profiles along the transect line indicated

480   by the white dashed line in Figure 7. The left profile plots displacements for the three

481   pressure distribution models using the dual-source scenario. Note that the maximum

482   difference between the curves is approximately 4 mm. The plot on the right shows three

483   curves all calculated using the model having pressure penetrating 300 m above the

484   reservoir, but with different values of the half-space shear modulus. The center curve

485   corresponds to the base half-space elastic model (shear modulus 3.38 GPa); the bottom

486   and top curves were calculated using shear modulus values double and half the base value,

487   respectively. The maximum difference between the upper and middle curves is similar to

488   the difference between the curves for the different models. This demonstrates that

489   relatively modest changes in the assumed elastic moduli introduce significant

490   uncertainties in calculated surface displacement amplitudes that can result in tradeoffs

491   with the depths of pressure perturbations. Uncertain poroelastic properties can also affect

492   surface displacement estimates but their effects were not evaluated in this study.

493

494   *3.14 Two-component Displacement Data*

495   Figure 9 shows the quasi-vertical and quasi-horizontal displacements generated by

496   Models 1 to 3 assuming the dual-source scenario. The quasi-vertical displacements are

497   similar to the range changes shown in Figure 6.   The horizontal displacement pattern

498   progressively rotates as the pressure perturbation penetrates to shallower depths, but the

499   difference between the Model 1 and 2 patterns is subtle. However, even though the

500   horizontal displacements produced by the given source geometry are less sensitive to the

501   height of the pressure plume, they add independent information to the inversion and

502   therefore hold some potential to improve vertical resolution.

503

504   In summary, the synthetic forward modeling described above leads to the following

505   general conclusions: (1) Dual-mode models that combine dilatational source restricted to

506   the horizontal reservoir with opening-mode sources restricted to a narrow tabular zone in

507   the caprock produce surface displacements that are most compatible with the InSAR

508   observations on the vicinity of KB-502, and therefore have potentially greater power to

509   resolve the vertical extent of pressure plumes. Conversely, it is difficult to discriminate

510   between the heights of pressure perturbations when only one mode of deformation occurs

511   in both the reservoir and the vertical zone; (2) uncertainties in elastic properties

512   introduce trade-offs that degrade the ability to resolve (in any inversion approach) the

513   vertical extent of a pressure plume; and (3) two-component displacement data hold some

514   potential for improving vertical resolution beyond that attainable with InSAR scalar

515   range changes. We further examine each of these factors in the following section by

516   carrying out MCMC inversions of the data calculated using the synthetic models.

517

518   **3.2** *Stochastic Inversions of Synthetic Data*

519   We carried out inversions of synthetic data to evaluate the impact of various sources of

520   uncertainty on the resolution of overpressure migration into the lower caprock. The

521   inversion domain encompasses the same volume as shown in Figure 3, and is discretized

522   into 30 x 25 x 50 grid cells in E, N and depth respectively (node spacing 200m x 200m x

523   20 m). For these inversions, we assume that the elastic properties of the reservoir and

524   caprock are uncertain, so at each iteration the shear modulus value is sampled from a

525   uniform distribution between 3.00 and 3.76 GPa, centered on the base value of 3.38 GPa

526   used to generate the synthetic data. The Poisson ratio is likewise sampled from a uniform

527   distribution between 0.27 and 0.285. The strike and dip of all opening fractures are fixed

528   at 315° and 90°, respectively.

529

530   The models produced by the inversion contain pressure perturbation amplitudes

531   distributed in 3D space. However, our main goal in this study was to estimate the

532   probability of pressure leakage. Thus, we chose to post-process the pressure models in

533   the posterior distribution to calculate the probability of pressure leakage away from the

534   reservoir and the images presented show probabilities rather than pressure. Alternatively,

535   one could use the pressure perturbation models to estimate the state (opening or closing)

536   of the fracture(s) and the contribution of fracture opening to the surface deformation.

537

538   The posterior pdf (solution) obtained from each inversion contains between 45,000 and

539   90,000 models. Each inversion used eight compute cores running for about 16 hours. To

540   carry out the resolution assessments we calculated two simple probability measures. In

541   the first of these, we selected the top 3% of the models in each pdf that best fit the data

542   and used this subset to estimate a measure of the probability that a pressure perturbation

543   is present at each node in the grid. These estimates are determined by counting the

544   number of models, mn that have non-zero pressure within each grid cell. The probability

545   measure is estimated simply by normalizing the counter value for each cell by the

546   maximum counter value. In other words, the probability that a pressure perturbation is

547   present within the cell having the greatest counter value is assumed to be 1.0, and the

548   probability measures for all the other cells are calculated relative to that cell.

549

550   Figure 10 shows the probabilities obtained by inverting synthetic LOS data from Models

551   1 to 3 and using the dual-source scenario.   The horizontal slices at reservoir level show

552   that cells having non-zero probabilities are largely confined within the lateral boundaries

553   of each model. Vertical smearing of the pressure perturbation is evident in the vertical

554   sections for Model 1 and 2, with probabilities greater than ~0.7 concentrated within the

555   vertical fracture zone, above the reservoir. These results indicate that we can expect the

556   horizontal resolution attainable by inversion of InSAR data to be significantly better than

557   the vertical resolution. However, for these representative synthetic cases, cells having

558   probabilities greater than 0.5 do not extend vertically more than about 200 m above the

559   upper boundaries of the two models, showing that the vertical resolution is only

560   moderately degraded. Similar results (not shown) are obtained for purely dilatational

561   synthetic models, but in these cases the cells having the highest probabilities are

562   systematically located above the reservoir layer and the solution for Model 1 is smeared

563   to a significantly greater height than in the dual-source case.

564

565   Results of inverting synthetic quasi-EW and quasi-vertical displacements are shown in

566   Figure 11. While these results reinforce the main conclusion that the resolution in the

567   solutions is better horizontally than vertically, it is perhaps surprising that, given the

568   additional information provided by the quasi-EW component, the vertical resolution is

569   significantly worse than that obtained from the equivalent LOS displacements, especially

570   above the top of Model 2. At present, we have not ascertained the cause of this.

571

572   The second probability measure employed estimates the probability that a pressure

573   perturbation extends to a given depth within the lower caprock, regardless of where that

574   occurs in the 3D grid. For this estimate the top 3% of the models in the posterior pdf that

575   best fit the data are again used. The number of nodes at each depth having non-zero

576   overpressure is counted and then normalized to the count for the reservoir level.

577   Therefore, the probability of a pressure perturbation at reservoir depth is 1.0, and the

578   probabilities at other depths are estimated relative to the reservoir. The resulting plot of

579   this probability measure as a function of depth provides a better vertical resolution metric

580   – and one that is easier to visualize - than the slices shown in Figures 10 and 11 because

581   all of the nodes at each depth contribute to a single probability estimate. Plots of this

582   second probability measure are shown in Figure 12.

583

584   Figure 12A shows the probabilities estimated for an inversion of synthetic LOS data

585   generated using the dual-source scenario. If the vertical resolution were perfect, the

586   curve for Model 1 (blue) would look like a delta function with probability 1.0 at the

587   reservoir depth and zero elsewhere (this is also applies to panels B-D). In fact, the

588   probability at the reservoir depth is 1.0 but non-zero at shallower depths; for example,

589   there is a probability of 0.6 that the plume extends to 1700 m depth, indicating somewhat

590   limited resolution, but a probability of only 0.1 that it extends to 1500 m and zero

591   probability that it extends to the HU. The Model 2 result (green) gives the probability of

592   the pressure perturbation being confined below 1500 m as 0.5, but the probability that it

593   reaches 1100 m is less than 0.05. For Model 3 (red) the probability of the plume reaching

594   depths as shallow as 950 m is 0.9 or higher, and 0.75 that it reaches the HU.

595

596   The probability curves in Figure 12B result from inversion of range changes using only

597   dilatational sources. The vertical resolution for Models 1 and 2 is significantly poorer

598   than achieved with the dual-source scenario. For example, the solution for Model 1 has a

599   probability of 0.6 that the pressure perturbation reaches a depth of 1600 m, compared

600   with 0.25 for the dual-source scenario. While the probability that in the Model 2 solution

601   the pressure perturbation is present at 1500 m - the correct upper limit - is much higher

602   than seen in Figure 12A, the pressure distribution is smeared vertically, resulting in much

603   higher probabilities also at depths as shallow as 1300 m.

604

605   Figure 12C shows the probabilities resulting from an inversion of two-component

606   displacements using the dual-source scenario. Comparing with Figure 12A, we see that

607   the blue and red curves are similar, suggesting that range change and two-component data

608   yield comparable vertical resolution for Models 1 and 3. In contrast, the curve for Model

609   2 is similar to that in Figure 12B above 1500 m, again indicating degraded vertical

610   resolution above this depth compared with the LOS solution in 12A and consistent with

611   the interpretation of Figure 11. However, the separation between the depths

612   corresponding to the highest probabilities (say above 0.75) is wider in Figure 12C, which

613   suggests that inversions of two-component data may be more effective in discriminating

614   between a pressure perturbation that is confined to the reservoir from one that extends a

615   few hundred meters above it.

616

617   These synthetic results strongly suggest that inversions of either scalar range change or

618   two-component displacement data should be capable of distinguishing a pressure

619   perturbation that approaches the HU from one contained below a depth of ~1500 m, and

620   probably even 100-200 m shallower. While the solutions derived for Models 1 and 2 are

621   distinct in these noise-free synthetic cases, the vertical resolution attainable with real data

622   is likely to be degraded so that it is less certain whether it will be possible to discriminate

623   between pressure perturbations that extend to different heights within the lower caprock

624   below a depth of about 1500 m. The results also suggest that two-component

625   displacements derived from InSAR may improve vertical resolution to some extent;

626   however, this conclusion is less than definitive, which may be consistent with the

627   relatively low sensitivity of horizontal displacement patterns to the different source

628   models (Figure 9). Finally, base models that include both opening-mode and dilatational

629   sources appear to be more effective in resolving the vertical extent of a pressure plume.

630

631   Considering the uncertainty in deriving elastic properties for In Salah discussed in the

632   Introduction, the ±11% variation in shear modulus assumed so far in inverting the

633   synthetic data is probably overly optimistic. Figure 12D shows the results of carrying out

634   the same inversion used to produce Figure 12C but sampling the shear modulus from a

635   uniform distribution between 1.69 and 6.76 GPa (-50% to +100%), which is probably

636   more realistic. These inversions also allowed random (uniform) variation in Poisson's

637   ratio in the range 0.27 – 0.285. The probability curves for Models 1 and 3 are fairly

638   similar to those in Figure 12C. The curves for Model 2 are markedly different; the effect

639   of the greater uncertainty is to flatten the curve so that the Model 1 and Model 2 curves

640   are much closer together (this is probably true in general for the entire range of

641   probabilities, as the steps at probability values of 0.45 and 0.75 are likely sampling

642   artifacts in this particular inversion). This suggests that it would be quite difficult to

643   discriminate between Models 1 and 2 given a large uncertainty in elastic properties.

644   However, even given an uncertainty as large as this, it should still be relatively easy to

645   discriminate both of the other models from Model 3.

646

647

648   # 4.0 STOCHASTIC INVERSIONS OF IN SALAH FIELD
649   # DATA

650
651   We inverted subsets of the In Salah InSAR data set over three time intervals beginning at

652   the inception of injection at well KB-502 in August 2005 and ending in August 2010.

653   We focused on the response to injection in KB-502 in order to provide a basis for

654   assessing the likelihood that the CO_2 plume penetrated above the storage volume into the

655   lower caprock, and, if so, the likely vertical extent of penetration. Since the inversions of

656   InSAR data constrain only changes in the fluid pressure or volume distribution in the

657   subsurface, they can provide information about the horizontal and vertical extents of

658   pressure perturbations that can be used indirectly, for example as constraints on flow

659   modeling, to investigate the distribution of actual CO_2 saturation.

660

661   The time periods covered by the three InSAR data sets are shown relative to the KB-502

662   injection history in Figure 13. All of the InSAR data, shown in Figure 14, were

663   processed by TRE and made available by the JIP. The data sets covering the time

664   intervals June 2005-August 2006, during the first phase of injection, and December 2007-

665   June 2008, during shut-in, comprise the Envisat C-band permanent scatterer (Ferretti et

666   al., 2001) range change data described by Vasco et al. (2008, 2010). The estimated

667   standard deviation of these data is in the range 1.0-2.5 mm (Rucci et al., 2010, 2013). The

668   third data set covers the time interval November 2009-July 2010 during the second

669   injection phase, and comprises quasi-EW and quasi-vertical displacements derived from

670   ascending and descending Cosmo-SkyMed (X-band) interferograms processed using

671   TRE's SqueeSAR^{TM} method, which integrates information from both permanent and

672   distributed scatterers (Ferretti et al., 2011). Rucci et al. (2013) describe the method used

673   to extract the two displacement components (from Envisat data in their case). The

674   standard deviations of the Cosmo-SkyMed displacement measurements are estimated to

675   be less than 3 mm (A, Rucci, TRE, personal communication). The range-change and

676   two-component displacement data were both re-sampled on to 100 m x 100 m grids.

677

678   *4.1 Model Set-up and Choice of Constraints*

679   We used the insights developed from the synthetic data inversions to guide the inversions

680   of the field data. The 3D inversion domain and grid are identical to those described above.

681   We first experimented with different inversion constraints and inversion set-ups (i.e. the

682   way pressure models are sampled) to evaluate their impacts on pressure perturbation

683   probability estimates.

684

685   Preliminary work (J. White, LLNL, personal communication) had indicated that the

686   Gemmer et al. (2012) reference model may overestimate the caprock stiffness, and that a

687   uniform reduction by a factor of 0.5 appeared to provide a better fit to observed range-

688   change amplitudes. Metrics generated as part of the MCMC procedure also indicted that

689   the lower stiffness values produced better fits to the data. Therefore, in the inversions

690   discussed below the shear modulus was sampled from a uniform distribution between 0.3

691   and 2.0 GPa.

692

693   Figure 15 shows probability estimates derived from the June 2005 – August 2006 range-

694   change data using various model set-ups. The curves indicate that the probability that the

695   pressure perturbation reached the HU is 10% or less regardless of the assumed constraints,

696   and the probabilities estimated from all of the solutions fall of rapidly across the bottom

697   400 m of the caprock (depth range 1400 – 1800 m). The results of inversions that

698   employed the dual-source scenario and six ellipsoids to represent the overpressure

699   distribution (green and blue curves) have a probability of about 0.5 that the pressure

700   perturbation is present at the Hot Shale (depth 1500 m), falling to 0.3 at 1400 m. The

701   inversion employing only dilatational sources (dashed curve) results in a probability of

702   0.25 at 1500 m.

703

704   In one of the trial inversions (solid blue line) the strike and dip of opening-mode sources

705   were randomly sampled from uniform distributions over the ranges ± 180° and ± 90°,

706   respectively. The opening-mode strike and dips for all models in the posterior pdf are

707   plotted in Figure 16. The two predominant modes in the strike histogram at about 130°

708   and 300°-325° are close agreement with the predominant fracture strike orientations

709   found by Iding and Ringrose (2010) from analysis of core and image logs from KB-502.

710   Iding and Ringrose reported that fractures are dominantly sub-vertical, which we interpret

711   as dips in the range 75°-90°. This range encompasses the two predominant peaks in the

712   dip histogram. The predominant strikes and dips recovered by the stochastic inversion

713   are also in reasonable agreement with those found by Rucci et al. (2013) to provide an

714   optimal fit to the InSAR data. Therefore, we judged it valid to constrain the strike and

715   dip used in the inversion to be 318° and 90°, respectively, in order to reduce the number

716   of degrees of freedom and trade-offs that might limit resolution. The probabilities that

717   result from applying these constraints are shown by the green curve in Figure 15.

718

719   The most significant differences remaining after applying the geometrical constraints are

720   the pressure perturbation probabilities at depths between 1300 m and 1550 m. Given the

721   apparently poorer vertical resolution obtained using only dilatational sources in the

722   synthetic tests, we elected to use the dual- mode scenario for the final inversions of the In

723   Salah data. Significant differences in the probabilities within the same depth range also

724 result from using a maximum of six compared with a maximum of three ellipsoids to

725 represent overpressure distributions. We chose to allow the inversions to use up to six

726 ellipsoids to provide better spatial sampling of pressures.

727

4.2 In Salah Inversions for Three Time Periods

729 Figure 17 shows probabilities that a pressure perturbation exists according to the first

730 probability measure described previously, calculated from the inverse solutions for the

731 three time periods defined in Figure 13. The top row in Figure 17 shows horizontal slices

732 at the reservoir level and the bottom row vertical slices along W-E transects for each time

733 period. Figure 18 shows probabilities that a pressure perturbation exists as a function of

734 depth (second probability measure) for the three periods. The blue curves result from

735 inversions that sample from a shear modulus range (2-7 GPa) that is representative of the

736 Gemmer et al. (2012) reference model, and are included for comparison with the

737 preferred range of 0.3-2.0 GPa.

738

739 The horizontal probability distribution for the 2005-2006 time period (Figure 17 top left)

740 during the initial injection images a narrow NW-trending zone intersecting the horizontal

741 injection interval of KB-502. The area defined by probabilities greater than 0.5,

742 corresponding to locations where the pressure perturbation is relatively well resolved, is

743 approximately 3 km long and 1 km wide, although the area of non-zero probability

744 extends about 3 km NW and 1 km SE of the well, respectively. The zone of highest

745 probability (0.75-1.0), corresponding to the highest resolution, is centered approximately

746 1.5 km NW of the well and is two grid cells (400 m) wide. In Figure 18, this high-

747 probability zone is confined within the lowest 150 m of the caprock, but there is a

748 probability of ~0.5 that the pressure perturbation extends upwards a further 150 m to

749 reach the Hot Shale. This result is in closely consistent with the fracture opening solution

750 of Vasco et al. (2010) and is also consistent with that of Rucci et al. (2013), although the

751 maximum fracture aperture opening in the latter solution is located only about 300 m NW

752 of the well. The probability that the pressure perturbation approaches within 150 m of

753   the HU is less than 0.15. Comparison of the green and blue curves indicates only a small

754   sensitivity above a depth of 1400 m to the assumed elastic properties.

755

756   The second set of probability plots correspond to a six-month snapshot of the negative

757   pressure changes that developed during the shut-in interval.   While there a slight

758   suggestion of pressure change NW of KB-502, the high probabilities in the solution are

759   tightly restricted to a small zone immediately SE of the well and within the lowest 100-

760   200 m of caprock.   This suggests that if the mechanism for fluid migration during

761   injection was indeed increased permeability owing to pressure-induced fracture opening

762   and/or hydrofracture, then closing of fractures in the lowermost caprock after shut-in may

763   have reversed the permeability change, thus allowing elevated pressures at shallower

764   depths to be maintained. In this case, pressure dissipation would only take place within

765   the relatively porous reservoir, resulting in the slowing decline of the wellhead pressure

766   seen in Figure 13, and the slow rate of surface subsidence observed in the InSAR data.

767

768   The amplitudes of surface displacements imaged during the second injection phase are a

769   factor of 4-5 smaller than the range changes observed during the first phase (Figure 14).

770   This is presumably a result of the lower overall injection pressures and rates during the

771   second phase compared with those during the selected time interval during the first

772   (Figure 13), although this is not clear. The reduction in signal-to-noise ratio results in

773   overall poorer resolution in the inversion solutions, and hence the relatively low

774   probability estimates seen in Figure 17.

775

776   The relatively high (> 0.3) probabilities in Figure 17 indicate that during the 9-month

777   period beginning at the start of the second injection in November 2009 positive pressure

778   changes were confined to two small zones, one in the vicinity of the toe of KB-502 and

779   an entirely new one west of the well. Patchy pressure changes within the zone NW of the

780   well predominantly associated with first phase of injection are imaged only with very low

781   probabilities. Figure 18 shows that, using the preferred (lower) range of shear moduli,

782   the highest probability of the presence of a pressure perturbation extends 100 m above the

783   top of the reservoir. During this phase the estimated probability that the perturbation is

784   present at the Hot Shale is 0.6, significantly higher than during the initial injection, and

785   there is a relatively high probability (0.4) that the perturbation extended to a depth of

786   1400 m. This is consistent with re-opening of pre-existing fractures after injection

787   resumed. The probability of pressure changes above 1200 m remains low (<0.15). In

788   this case there is a wide separation between the curves above 1500 m corresponding to

789   the inversions using the different elastic models, and hence increased overall uncertainty

790   in the inverse solutions. This increased sensitivity is likely a result of the relatively low

791   signal-to-noise ratio of the data.

792

793

794   **5.0 CONCLUSIONS**

795   Maps of InSAR line-of-sight range changes and displacements derived from synthetic

796   aperture data collected over In Salah during two injection phases and the intervening

797   interval have provided one of the most important data sets used in investigating the

798   migration of CO_2 and other fluids within the storage complex and possibly into the

799   overlying lower caprock. In particular, inversion and forward modeling constrained by

800   these data provide evidence suggesting that changes in fluid pressure and CO_2 saturation

801   extended to some height above the reservoir within a narrow, sub-vertical high-

802   permeability zone. However, the vertical extent of the pressure perturbation - and hence

803   the height of the CO_2 plume - remains a matter of debate because it is poorly resolved by

804   results published to date. This stems from tradeoffs inherent in modeling surface

805   displacements produced by subsurface deformation sources when the (assumed known)

806   parameters used as prior constraints are uncertain.

807

808   We carried out a series of systematic studies to further evaluate parameter sensitivity and

809   sources of non-uniqueness given the InSAR data set and inversion/modeling constraints

810   and their uncertainties specific to the In Salah operation. The primary objective of the

811   study was to place probabilistic bounds on the vertical extent of the pressure perturbation

812   during each phase of injection at well KB-502. To this end, we carried out stochastic

813   inversions of both synthetic and field data that produce as solutions probability density

814   functions over the space of alternative models that are consistent with the data and with

815   the prior constraints. Each inversion run used 8 compute cores running for 16 hours.

816

817   Synthetic forward modeling and inversions indicated that, of those tested, the most likely

818   subsurface deformation scenario to apply to In Salah is one in which dilatational

819   (isotropic inflation/deflation) sources and tensional opening/closing of fractures (Mode I)

820   are confined to the reservoir and the sub-vertical tabular zone above the reservoir inferred

821   from 3D seismic, respectively. This combination also yields the best vertical resolution

822   in inverse solutions. The most robust conclusion from the synthetic study is that

823   inversions of the In Salah data should be easily capable of discriminating pressure

824   perturbations that approach the top of the lower caprock at the Hercynian Unconformity

825   from those that are confined below a depth of 1400-1500 m. The synthetic results also

826   suggest that there is a moderate chance of discriminating a perturbation at ~1500 m from

827   one confined to the vicinity of the reservoir, but this conclusion is less certain given the

828   present large uncertainties in elastic properties (and noisy data).

829

830   We carried out stochastic inversions of the In Salah field data using the inversion set-up

831   and set of optimal prior constraints deduced from the synthetic study and initial

832   application to the data themselves. From the probability solution for the first injection

833   phase we can conclude with a high degree of confidence that pressure change was

834   confined to a well-defined NW-trending zone intersecting KB-502 and was concentrated

835   to the NW of the well, and that it is very unlikely that a pressure perturbation approached

836   within 150 m of the Hercynian. There is a high probability that the pressure change

837   extended into the lowest 150 m of the caprock, and moderate (50%) probability that

838   reached as far as 1500m depth. These results are closely consistent with recently

839   published deterministic inverse solutions.

840

841   The inversions also provide interesting information about the pressure distributions

842   during the 2007-2009 well shut-in and during the second injection phase. The spatial

843   probability distribution indicates that depressurization over a 6-month period beginning

844   six months after shut in was tightly restricted to a small zone SE of the well and, at a 50%

845   probability level, extending ~200 m above the reservoir. During the first eight months of

846   the second injection, elevated pressures appear to have been confined to two small zones,

847   one at the toe of the well and the other 1-2 km to the west. In this case, the maximum

848   probability of a pressure-perturbation extends 100-200 m above the reservoir and there is

849   a 60%-70% probability that is reaches the Hot Shale.   Although the relatively low

850   signal-to-noise ratio of the data reduces the reliability of the inverse solution, we believe

851   that there it is still very unlikely that the pressure change approached the HU during this

852   time interval. The inversion results for both of these later time intervals may shed further

853   light on the mechanics of permeability creation and subsequent flow in the lower caprock

854   and reservoir.

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857   **Acknowledgements**

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872   **REFERENCES**

873   Burgmann, R., P. Rosen, and E.J. Fielding (2000), Synthetic aperture radar

874   Interferometry to measure Earth's surface topography and its deformation, *Ann. Rev.*

875   *Earth. Planet. Sci.*, **28**, 169-209.

876

877   Davis, E., (2011), Analysis of surface deformation at the In Salah CO_2 sequestration

878   project, in *Proc. 10th Ann. Conf. on Carbon Capture and Sequestration*, Pittsburgh,

879   PA, May 2-5.

880

881   Ferretti, A., C. Prati, and F. Rocca (2001), Permanent scatterers in SAR interferometry,

882   *IEEE Trans. Geosci. Remote Sens.*, **39**, 8 –20.

883

884   Ferretti, A., A, Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci (2011)

885   A new algorithm for processing interferometric data-stacks: SqueeSAR

886   *IEEE Trans. Geosci. Remote Sens.*, **49**, 3460–3470.

887

888   Fjaer, E. (2009), Static and dynamic moduli of weak sandstone, *Geophysics*, **74**, WA103-

889   Wa112.

890

891   Gemmer, L, O. Hansen, M. Iding, S. Leary, and P. Ringrose (2012), Geomechanical

892   response to CO_2 injection at Krechba, In Salah, Algeria, *First Break*, **30**, 79-84.

893

894   Gibson-Poole, C. M., and S. Raikes (2010), Enhanced understanding of CO_2 storage at

895   Krechba from 3D seismic, in *Proc. 9th Ann. Conf. on Carbon Capture and*

896   *Sequestration*, Pittsburgh, PA, May 10-13.

897

898   Green, A., and I. Sneddon (1950), The distribution of stress in the neighborhood of a flat

899   elliptical crack in an elastic solid, *Math. Proc. Cambs. Phil. Soc.*, **46**, 159-163.

900   Iding, M., and P. Ringrose, (2010) Evaluating the impact of fractures on the performance

901   of the In Salah CO_2 storage site, *Int. J. Greenhouse Gas Control*, **4**, 242 – 248.

902

903   Li, L., and E. Fjaer, Modeling of stress-dependent static and dynamic moduli of week

904   sandstones (2012), *J. Geophys. Res.*, **117**, B05206, doi:10.1029/2011JB009019.

905

906   Metropolis, N., A. Rosenbluth, M. Rosenbluth, A. Teller, and E. Teller (1953), Equation

907   of state calculations by fast computing machines, *J. Chem. Phys.*, *1*, no. 6, 1087-1092.

908

909   Morris, J.P., Y. Hao, W. Foxall, and W. McNab (2011), A study of injection-induced

910   mechanical deformation at the In Salah CO_2 storage project, *Int. J. Greenhouse Gas

911   Control*, **5**, 270-280.

912

913   Mosegaard, K., and A. Tarantola (1995), Monte Carlo sampling of solutions to inverse

914   problems, *J. Geophys. Res.*, **100**, 12431-12447.

915

916   Mura, T. (1987), *Micromechnics of Defects in Solids*, 2nd Ed., Kluwer, Dordrecht,

917   Netherlands, 587p.

918

919   Okada, Y. (1985), Surface deformation due to shear and tensile faults in a half-space,

920   *Bull. Seismol. Soc. Am.*, **75**, 1135-1154.

921

922   Okada, Y. (1992), Internal deformation due to shear and tensile faults in a half-space,

923   *Bull. Seismol. Soc. Am.*, **82**, 1018-1040.

924

925   Onuma, T. and S. Ohkawa (2009), Detection of surface deformation related with CO_2

926   injection by DInSAR at In Salah, Algeria, *Energy Procedia*, **1**, 2177-2184,

927

928   Onuma, T., K. Okada, and A. Otsubo, 2011, Time series analysis of surface deformation

929   related with CO_2 injection by satellite-borne SAR Interferometry at In Salah, Algeria,

930   *Energy Procedia*, **4**, 3428-3434.

931

932   Ramirez, A, J. Nitao, W. Hanley, R. Aines, R. Glaser, S. Sengupta, K. Dyer, T. Hickling,
933   and W. Daily (2005), Stochastic Inversion of Electrical Resistivity Changes Using a
934   Markov Chain, Monte Carlo Approach, *J. Geophys. Res.*, **110**, B02101,
935   doi:10.1029/2004JB003449.

937   Rinaldi, A. P., and J. Rutqvist (2013), Modeling of deep fracture zone opening and
938   transient ground surface uplift at KB-502 injection well, In Salah, Algeria, *Int. J.*
939   *Greenhouse Gas Control*, **12**, 155-167.

941   Ringrose, P., M. Atbi, D. Mason, M. Espinassous, O. Myhrer, M. Iding, A. Mathieson,
942   and I. Wright (2009), Plume development around well KB-502 at the In Salah CO_2
943   storage site, *First Break*, **27**, 85–89.

945   Rosen, P.A., S. Hensley, I.R. Joughin, F.K. Li, S.O. Madsen, E. Rodriguez, and R.M.
946   Goldstein (2000), Synthetic aperture radar interferometry, *Proc. IEEE*, **88**, 333-382.

948   Rucci, A., D.W. Vasco, and F. Novali (2013), Monitoring the geologic storage of carbon
949   dioxide using multicomponent SAR interferometry, *Geophys. J. Int.*, **193**, 197-208.

951   Rutqvist, J., HJ-H Liu, D.W. Vasco, L. Pan, K. Kappler, and E. Majer (2011), Coupled
952   non-isothermal, multiphase fluid flow, and geomechanical modeling of surface
953   deformations and potential for induced seismicity at the In Salah CO_2 storage
954   operation, *Energy Procedia*, **4**, 3542-3549.

956   Shi, J-Q., C. Sinayuc, S. Durucan, and A, Korre (2012), Assessment of carbon dioxide
957   plume behavior within the storage reservoir and the lower caprock around the KB-
958   502 injection well at In Salah (2012), *Int. J. Greenhouse Gas Control*, **7**, 115-126.

960   Vasco, D. W., A. Ferretti, and F. Novali (2008), Estimating permeability from quasi-
961   static deformation: Temporal variations and arrival-time inversion, *Geophysics*, **73**,
962   O37– O52.

963

964 Vasco, D. W., A. Rucci, A. Ferretti, F. Novali, R. C. Bissell, P. S. Ringrose, A. S.

965   Mathieson, and I. W. Wright (2010), Satellite-based measurements of surface

966   deformation reveal fluid flow associated with the geological storage of carbon

967   dioxide, *Geophys. Res. Lett.*, **37**, L03303, doi:10.1029/2009GL041544.

968

969 Wright, I. (2006), Two years of geologic storage at In Salah, in *Proc. 8th Int. Conf. on*

970   *Greenhouse Gas Control Technology, Trondheim, Norway, 19-22 June.*

971

972 Wright, T.J., B.E. Parsons, and Z. Lu (2004), Toward mapping surface deformation in

973   three dimensions using InSAR, *Geophys. Res. Lett.*, **31**, 1-5.

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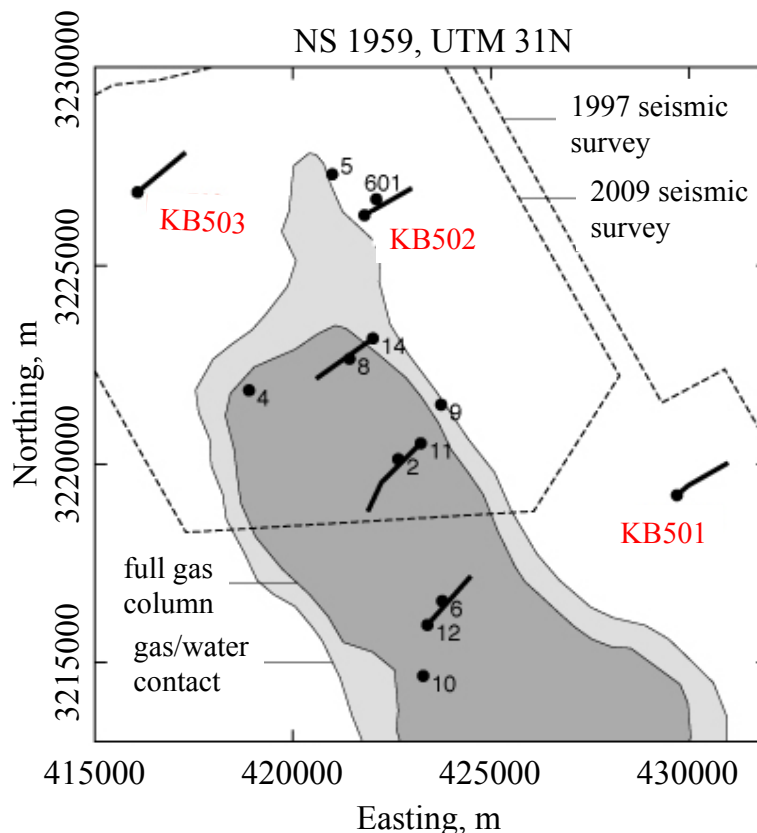
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977 **Figure 1**: Layout of the Krechba field. Injector wells labeled in red.
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~170 m

~900 m · Hercynian Unconformity

C20.7 Hot Shale

~1880 m → C10.3
~1900 m → C10.2 · Reservoir
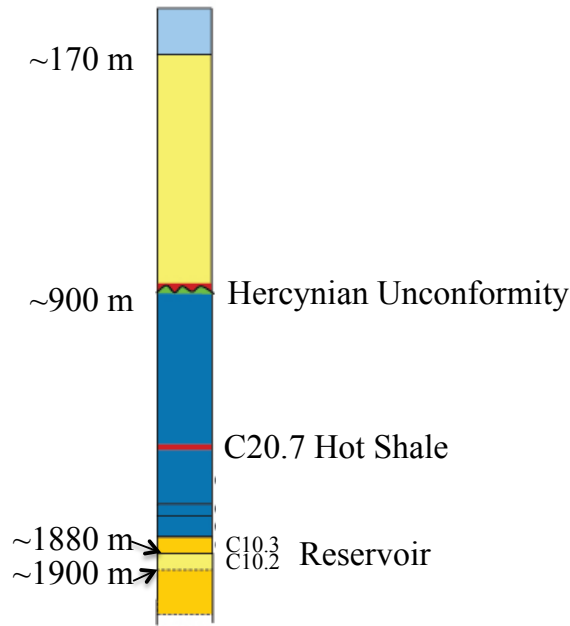
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982 **Figure 2**: Krechba stratigraphy (courtesy In Salah JIP).
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Top view

Side view

5 km

6 km

Depth range:
0.85 − 1.87 km

6 km

probability

0.0   1.0
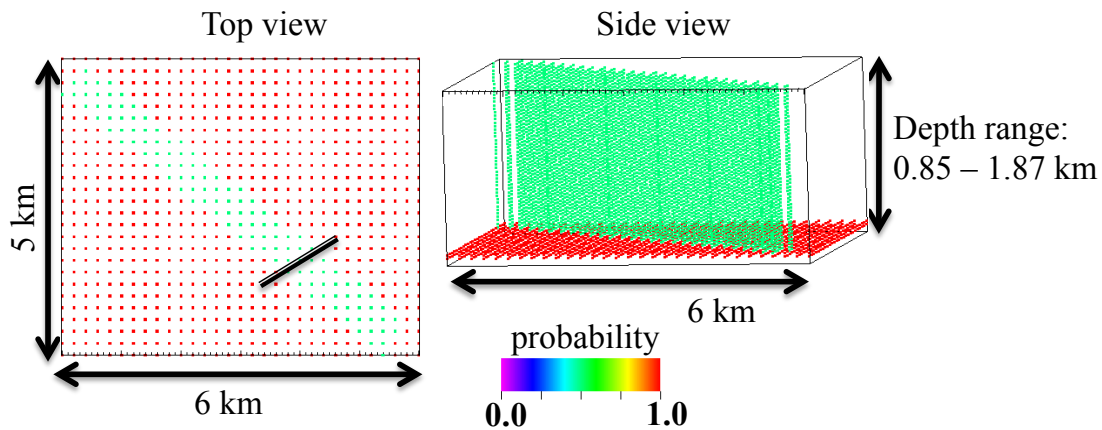
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995 **Figure 3**: Structural model used in synthetic modeling and stochastic inversions. The
996 model assumes that it is certain that overpressures will exist in the reservoir (red nodes)
997 and probable that the plume will penetrate the vertical zone within the reservoir and
998 lower caprock (green nodes). The horizontal black line shows the approximate location of
999 the KB-502 injection interval.

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1014   **Figure 4**: Schematic of the MCMC procedure as adapted for inversion of In Salah
1015   InSAR data. The process starts (upper left) by proposing pressure plume realizations that
1016   honor simple rules. Realizations that are consistent with the reservoir model (step B) are
1017   used to predict InSAR data (step E). Realizations that produce InSAR data that are
1018   acceptably close to the observations become part of the posterior distribution.
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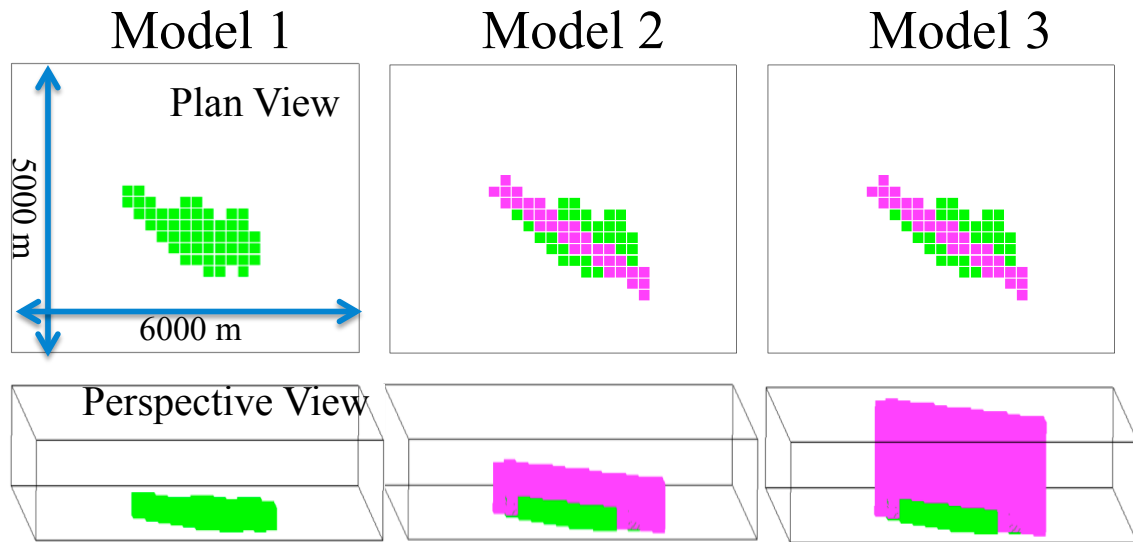
Figure 5: Plan (*top*) and perspective (*bottom*) views of the 3 three overpressure models used in the synthetic modeling. The height of the box is 1020 m. The *green* and *pink* elements indicate the pressurized regions in the reservoir layer and vertical zone, respectively: Model 1 (*left*), overpressure zone is fully contained within the reservoir; Model 2 (*center*), overpressure extends 300 m above the reservoir into the lower cap rock; Model 3 (*right*), overpressure extends 940 m from the reservoir to reach the HU.

A: Dilatational sources in reservoir and cap-rock

B: Mode I sources in reservoir and cap-rock

C: Dilatational in reservoir, Mode I sources in cap-rock
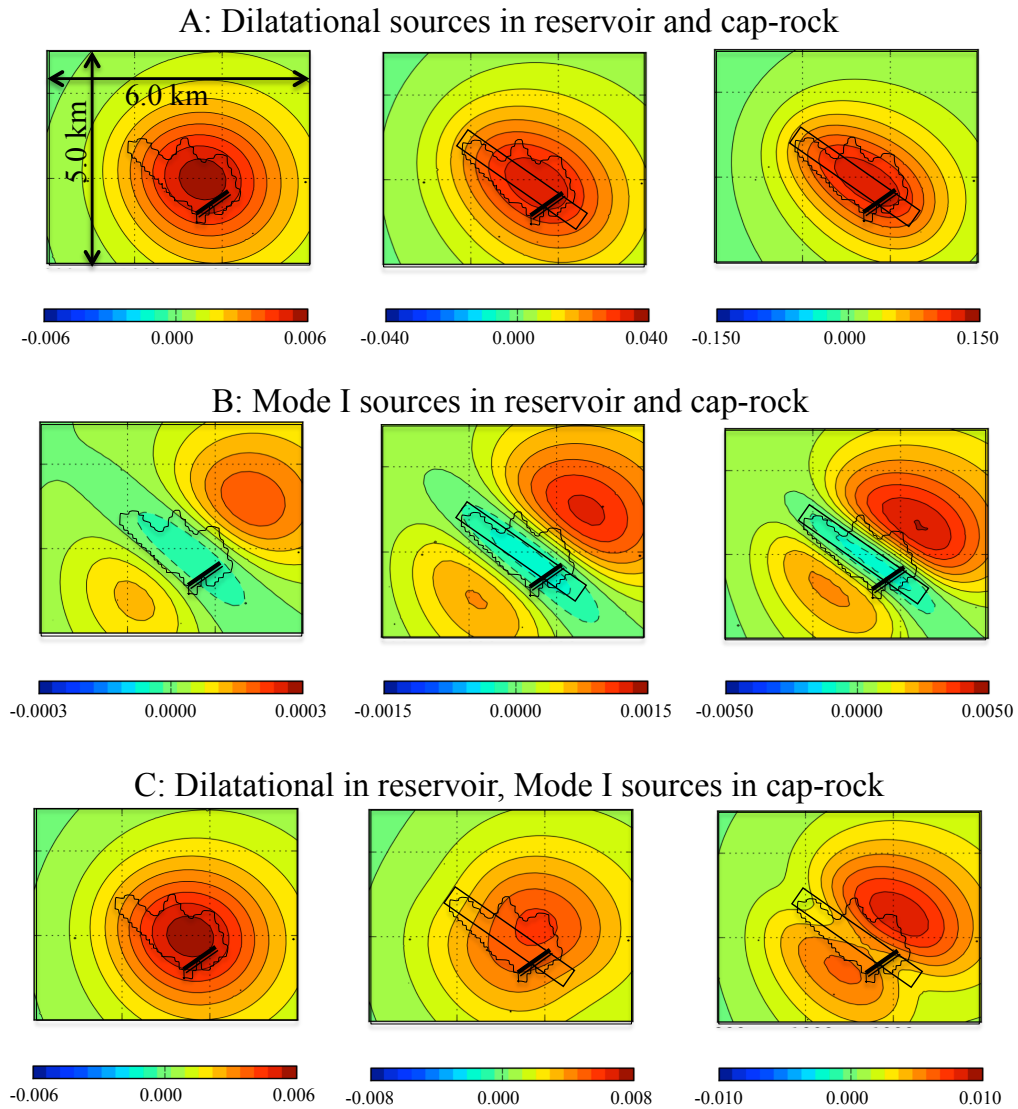
1040
1041
1042 **Figure 6**: Calculated InSAR range change for Models 1 - 3 (*left* to *right*) for 3
1043 deformation scenarios: (*A*) all deformation sources in reservoir and cap-rock are
1044 dilatational; (*B*) all deformation sources in reservoir and cap-rock are Mode I; and (*C*)
1045 deformation sources in the reservoir are dilatational and Mode I in the cap-rock. Positive
1046 range change indicates that the distance between the satellite and the surface is shorter;
1047 i.e. uplift. Note that the color scale (range change in m) is different for each of the images.
1048 The irregular thin black lines superimposed on the images show the outlines of the
1049 overpressure plumes. The thick black line shows the location of a hypothetical injection
1050 well.
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Figure 7: Comparison between observed range changes derived from Envisat data above KB-502 between March and July 2007 (*left*) with synthetics calculate from dilatational and Mode I sources in the reservoir and fracture zone, respectively (*middle*), and Mode I source in both the reservoir and fracture zone (*right*). The dashed line on the *middle* panel shows the transect line used for Figure 8.

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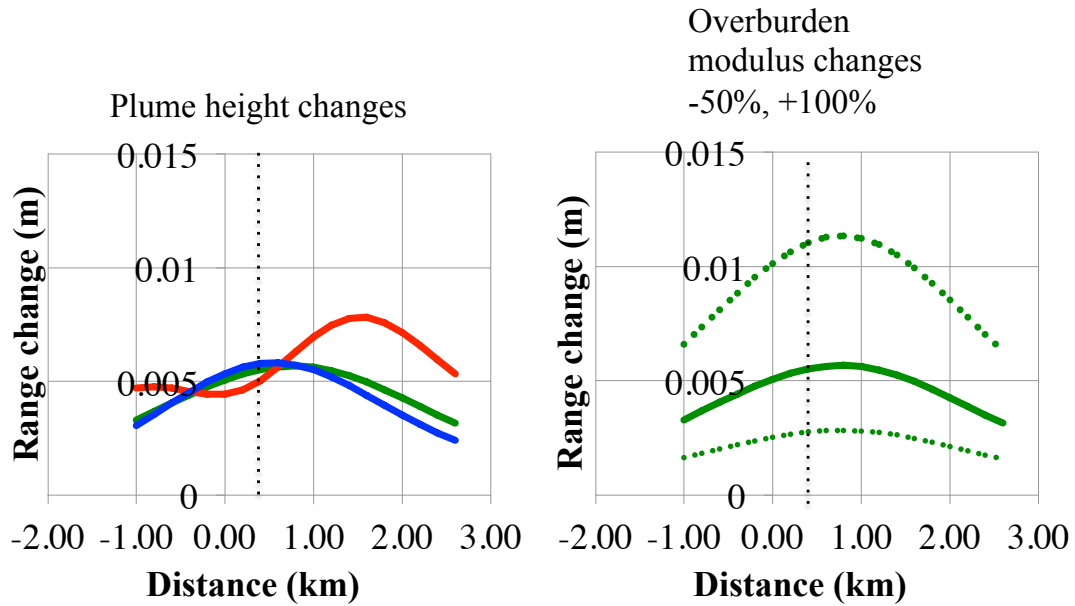
Figure 8: Sensitivity of InSAR range change to uncertainties in overburden properties. (*left*) variation in line-of-sight range change along the transect line shown in Figure 7 for the three dual-source models. (*right*). Variation in range change along the same transect for Model 2 (pressure penetrates 300 m above the reservoir) calculated for the base half-space elastic model (*solid curve*), and double (*dotted*) and half *dashed*) the base shear modulus value. The black dotted line indicates the position of the vertical fracture zone.

Easterly displacement   Vertical displacement

Model 1
6.0 km
5.0 km

-0.006   0.000   0.006

Model 2

-0.008   0.000   0.008

Model 3

-0.010   0.000   0.010
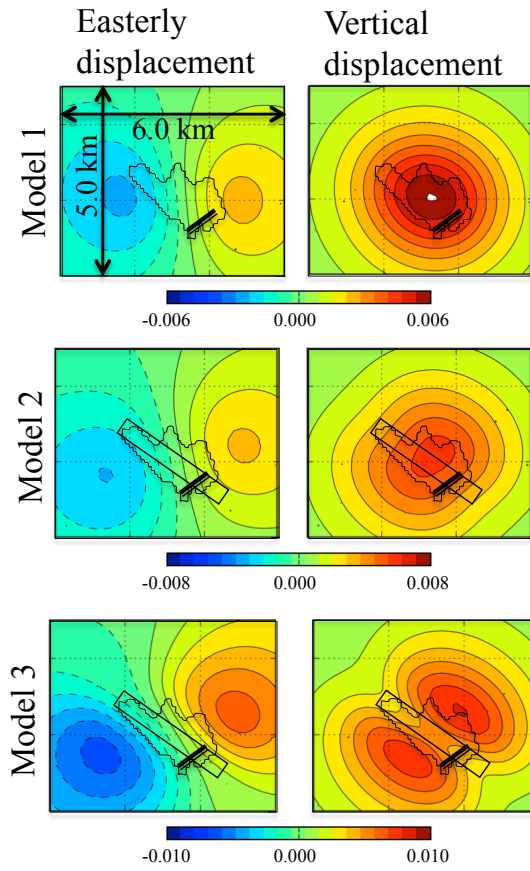
Figure 9: Quasi-easterly *(left)* and quasi-vertical displacements *(right)* calculated for models 1 - 3 (top to bottom) and the dual-mode scenario. Positive vertical displacements indicate uplift and positive Easterly displacements indicate movement to the East. Each color scale shows displacement in meters and is different for each row of images.
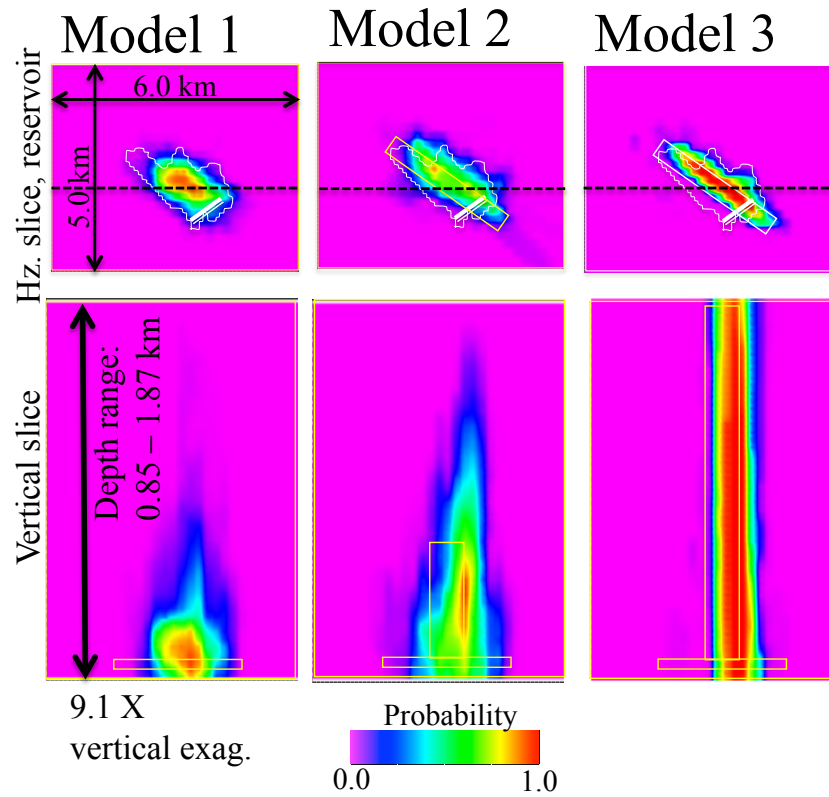
Figure 10: Results of inverting synthetic InSAR range-change data generated by the three synthetic reservoir models shown in Figure 5 and a dual-source scenario. The plots show the probability that the pressure plume exists at each node in the inversion grid (see text). (*top*) horizontal slices located at reservoir depth. White outlines superimposed on each plot outline the true shape of the pressure perturbation at the depth of the slice. The dashed line shows the location of vertical slices (*bottom*) (vertical exaggeration 9x).
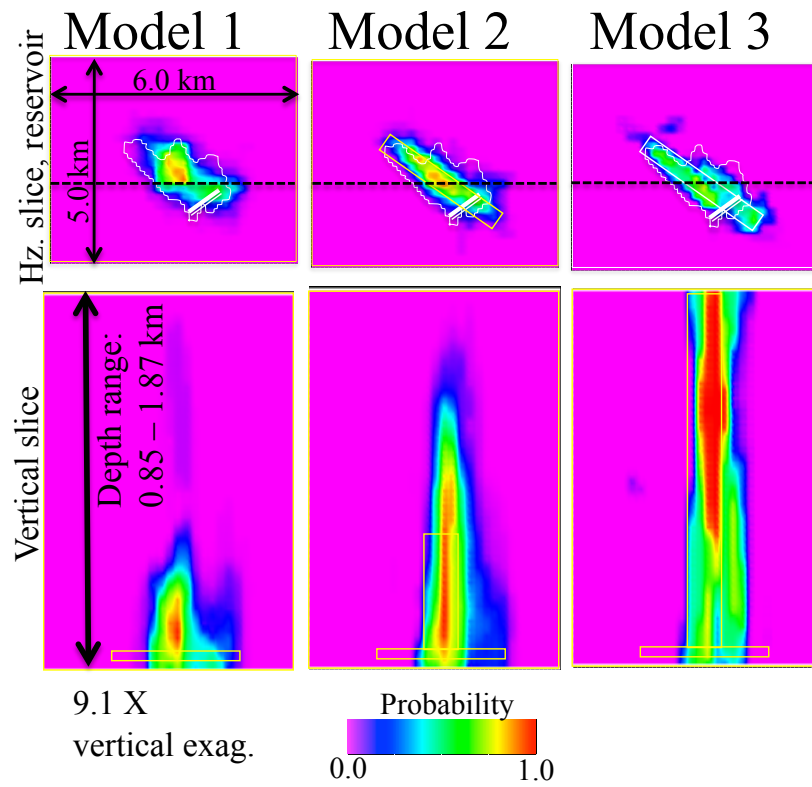
Figure 11: Results of inverting synthetic two-component displacements generated as for Figure 10. See Figure 10 caption for explanation.
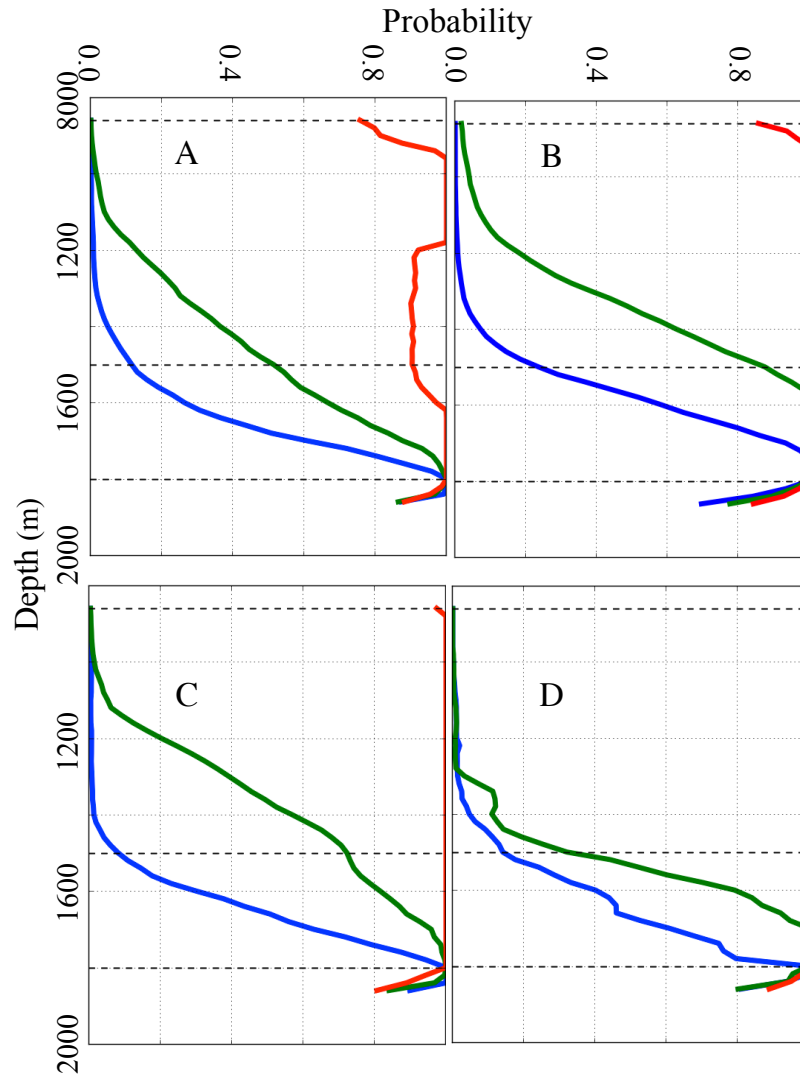
Figure 12: Estimates of probability that a pressure perturbation exists in the synthetic inverse solutions from: (*A*) LOS data and a dual-source scenario; (*B*) LOS and dilatational source only; (*C*) quasi-EW and quasi-vertical displacements and a dual-source scenario; (*D*) as in *C* with shear modulus uncertainty of -50% to +100% (the shear modulus variation for (*A*, B, *C*) is ± 11%). *Blue*, *green*, and *red* curves correspond to Models 1, 2 and 3, respectively. Dashed horizontal lines indicate, from deep to shallow, the tops of Models 1 (top reservoir), 2 (300 m above reservoir) and 3 (940 m above reservoir).

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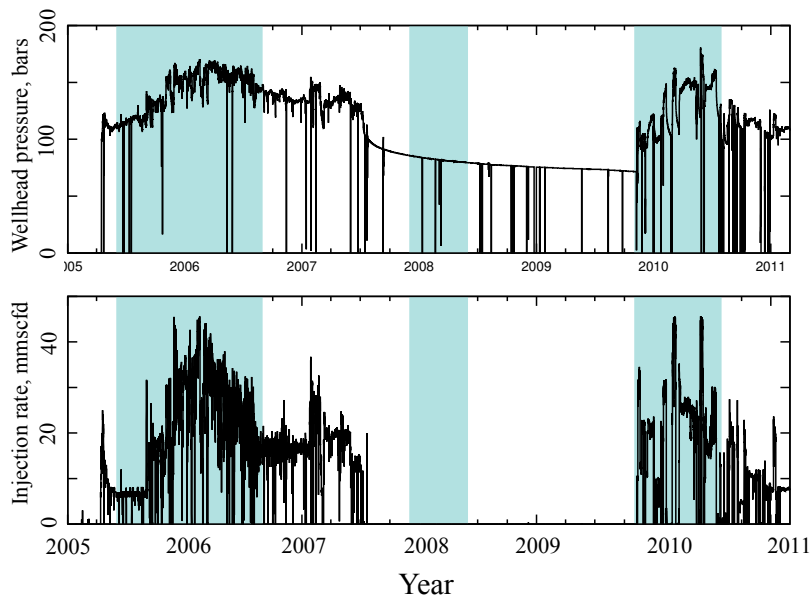
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1163 **Figure 13**: KB-502 wellhead pressure (top) and injection rate (bottom) as a function of
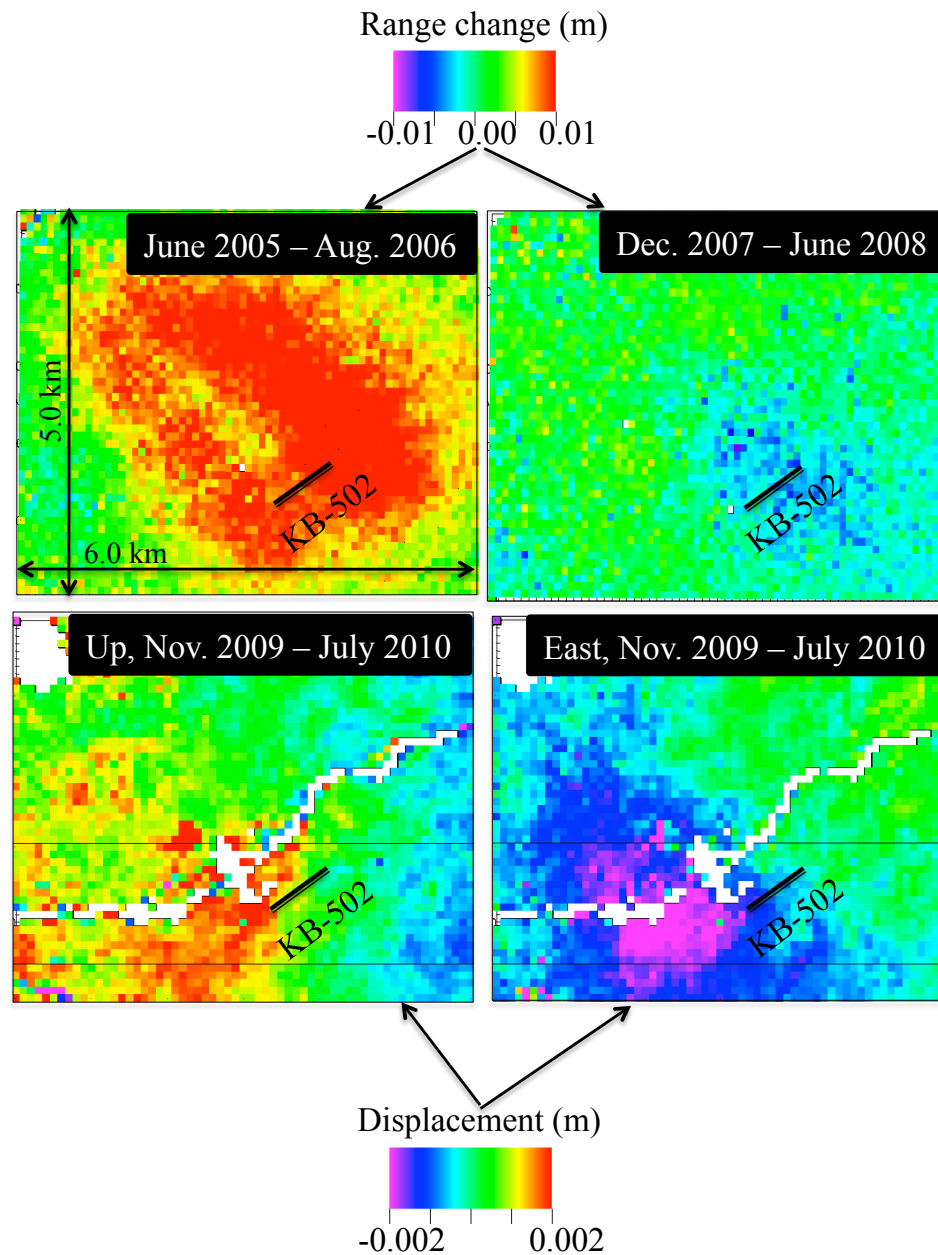1164 time. The light blue boxes define the time intervals of the In SAR images used for the
1165 inversions.
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Range change (m)

-0.01 0.00 0.01

June 2005 – Aug. 2006

Dec. 2007 – June 2008

5.0 km

6.0 km

KB-502

KB-502

Up, Nov. 2009 – July 2010

East, Nov. 2009 – July 2010

KB-502

KB-502

Displacement (m)

-0.002 0.002

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1176   **Figure 14**: InSAR images used for inversions over three time periods. (*top*) Envisat
1177   Track 294 PSInSAR range changes between June 2005 and August 2006 (*left*) and
1178   December 2007 and June 2008 (*right*). (*bottom*). Quasi-vertical (*left*) and quasi-east-west
1179   (*right*) displacements derived from SqueeSAR® processing of Cosmos-SkyMed data.
1180   The white colored pixels have been removed because they show displacements that are
1181   likely associated with surface processes such as seasonal moisture changes in wadis.
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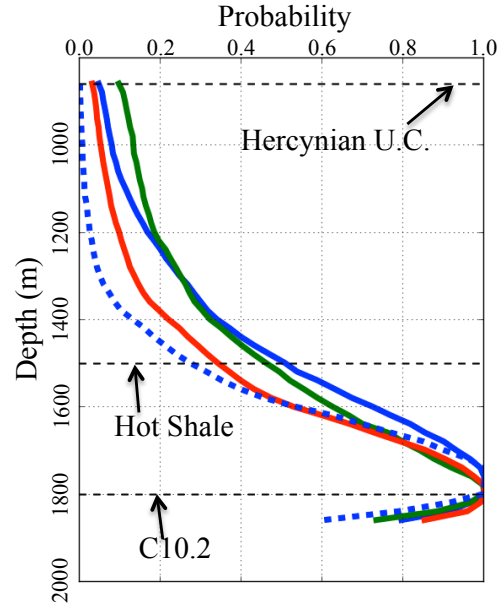
Figure 15:   Probability that the pressure plume extends to different caprock depths
derived from inversion of range-change data for the period 6/2005 – 8/2006. *Solid* curves
correspond to inversions using the dual-source scenario. The inversion corresponding to
the *solid blue* curve allowed the strikes and dips of opening-mode sources to vary, while
in the inversions resulting in the *green* and *red* curves they were held fixed at the strike
and dip reported by Iding and Ringrose (2012). *Dashed* curve corresponds to an
inversion using only dilatational sources. The depths of the reservoir (C10.2), Hot Shale,
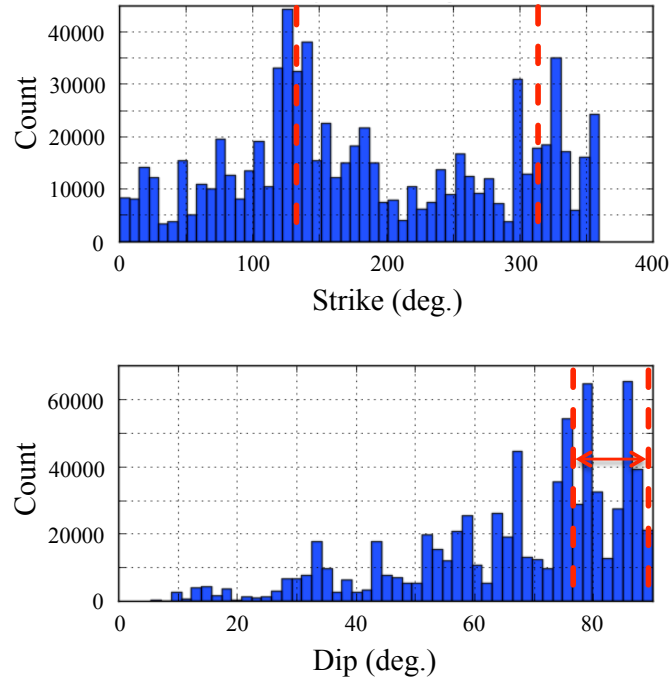and HU are shown for reference.

Figure 16: Histograms of strike (*top*) and dip (*bottom*) recovered by a stochastic inversion in which the strikes and dips of opening-mode sources were sampled from uniform distributions over the ranges ± 180° and ± 90°, respectively. The red dashed lines indicate the predominant fracture strike and dip angles reported by Iding and Ringrose (2010).
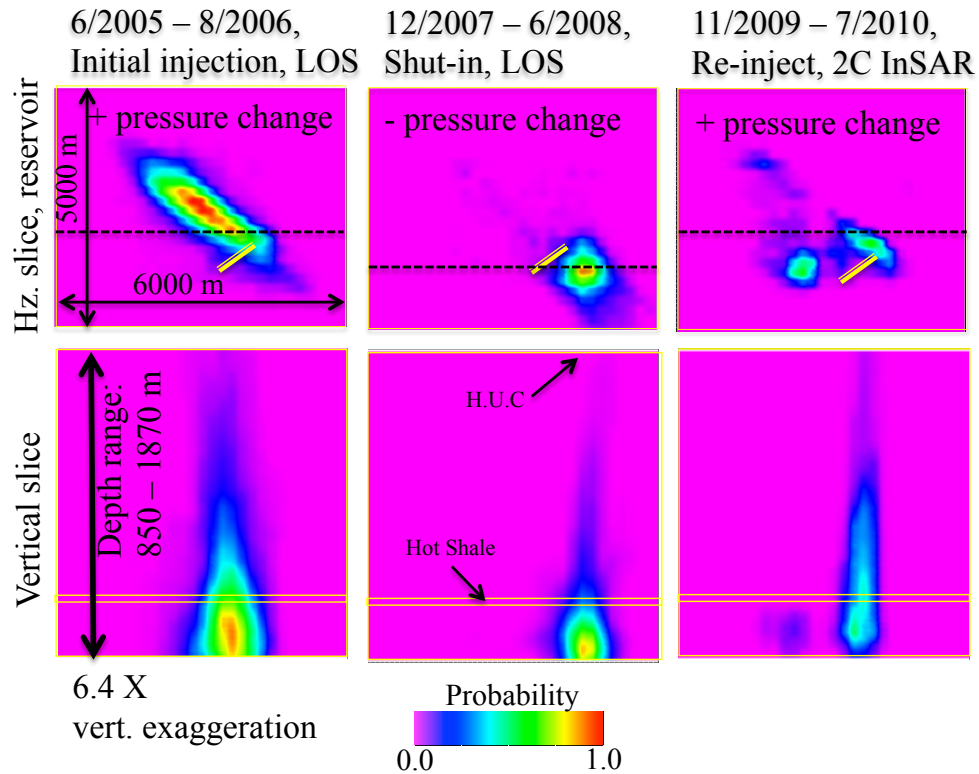
6/2005 – 8/2006,
Initial injection, LOS

12/2007 – 6/2008,
Shut-in, LOS

11/2009 – 7/2010,
Re-inject, 2C InSAR

Hz. slice, reservoir

+ pressure change

5000 m

6000 m

- pressure change

+ pressure change

Vertical slice

Depth range:
850 – 1870 m

H.U.C

Hot Shale

6.4 X
vert. exaggeration

Probability

0.0   1.0

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1216   **Figure 17**: Inversion results using In Salah field data during the initial injection (*left*),
1217   during shut-in (*center*), and during the early part of the second injection phase (*right*).
1218   The plots show the probability that a pressure perturbation exists at each node in
1219   horizontal slices through the inversion grid at reservoir depth (*top*) and in vertical slices
1220   (*bottom*); dashed lines show the locations of the vertical slices. A short yellow line
1221   identifies the KB-502 injection interval. Vertical slices show approximate locations of
1222   the Hot Shale and Hercynian Unconformity; the reservoir layer is located just above the
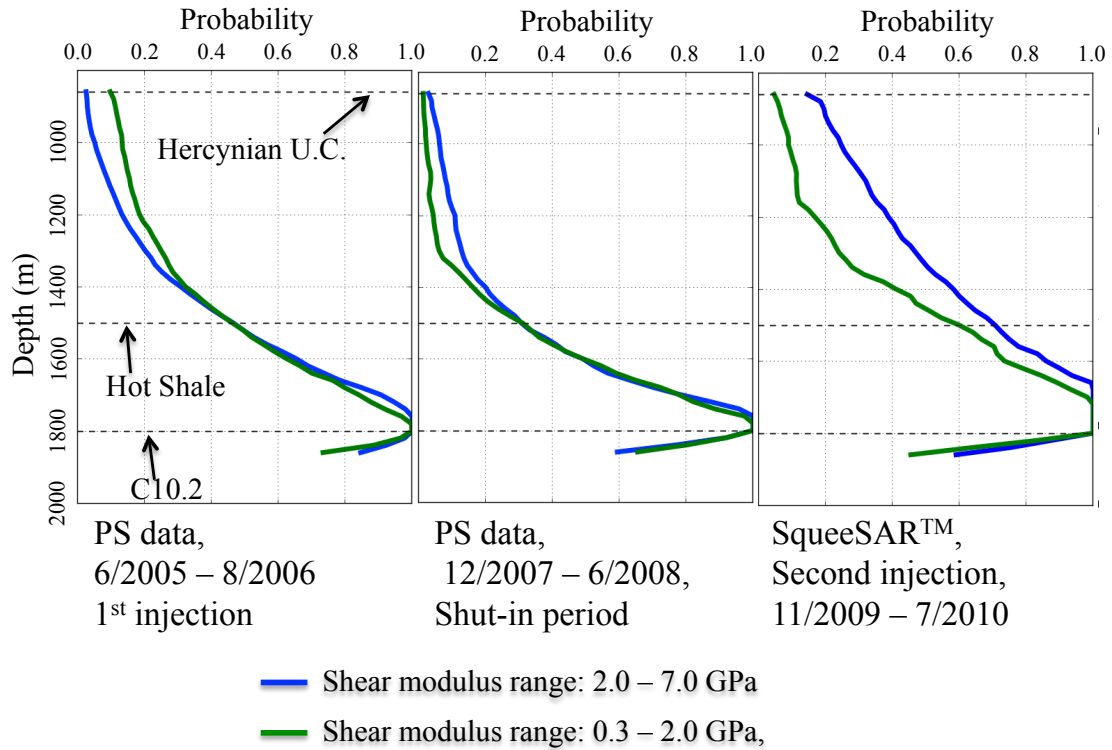1223   bottom edge of each slice.
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Figure 18: Estimated probability that the pressure plume extends to different cap-rock depths for the three time periods defined in Figure 11. The *green* and *blue* curves show estimates assuming two different shear modulus ranges, 0.3 – 2.0 GPa and 2.0 – 7.0 GPa, respectively.

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